SECTION NEWS

GEOMAGNETISM & PALEOMAGNETISM

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Magnetic Microscopy Promises a Leap in Sensitivity and Resolution

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Twenty years ago, Kirschvink argued that many paleomagnetic studies were limited by the sensitivity of the magnetometer systems then in use [*Kirschvink*, 1981]. He showed that sedimentary rocks could preserve detrital remanent magnetizations at levels of 10^{-14} to 10^{-15} Am^2, about 100–1000 times below the noise level of today's best superconducting (SQUID) rock magnetometers. If a more sensitive magnetometer could be built, it would dramatically expand the range and variety of rock types amenable to paleomagnetic analysis. Just such an instrument is now on the horizon: the low-temperature superconductivity (LTS) SQUID Microscope.

The LTS SQUID Microscope is the end-product of more than a decade of work on the application of high-resolution SQUID magnetometers for cardiology research by Franz Baudenbacher and John Wikswo of Vanderbilt University [*Wikswo*, 1996]. Its current prototype, the Ultra High Resolution Scanning SQUID Microscope (UHRSSM), maps the vertical component of the magnetic field above the surface of a sample at room temperature and pressure. It achieves this with a spatial resolution of 250 μm and a moment sensitivity (i.e., minimum detectable dipole moment) 10,000 times that of the most recent 2G Enterprises® Superconducting Rock Magnetometer (2G® SRM). The art of LTS SQUID microscopy has now progressed to the point that the fields of samples placed within the vacuum region of some instruments can be measured with spatial resolutions of only several micrometers.

Although magnetic force microscopes (MFMs) have better moment sensitivities than SQUID microscopes, the current generation of SQUID microscopes have field sensitivities 10^5 times better than MFMs and do not suffer from the sample-instrument interactions that plague MFM-sensing of magnetically soft materials. These interactions make MFMs difficult to use for quantitative measurements of the magnetic field above samples. Although it has ~10,000 times lower spatial resolution than a typical MFM, the UHRSSM is able to quantitatively map the magnetic fields of rock slices and thin sections at spatial resolutions 10–100 times better than that of the best existing SQUID rock magnetometers. It can therefore provide data with a resolution comparable to that of other common petrographic techniques such as optical and electron microscopy (Figure 1). This bridges the roughly six-orders-of-magnitude gap in spatial resolution between 2G® SRMs and MFMs, such that magnetization can be directly correlated with distinct minerals and textures.

Both the UHRSSM and 2G® SRM use similar commercially-available DC-SQUIDs operating at or near their thermal noise limits. So how can the SQUID microscope achieve such superior sensitivity at such high spatial resolution? Much of the answer lies in the closed geometry of dipolar magnetic fields and how their detection depends upon instrument size.

First, consider the 2G® 755 SRM (Figure 2a). A room-temperature sample is inserted into the middle of several ~8-cm diameter Helmholtz-style pickup coils held at 4 K. The large temperature difference between the sample and the coil requires shielding the coils within a dewar, heat-sunk radiation baffles, and many layers of superinsulation. Because they need to encircle both these structures and the sample, the coils need to be rather large in size. Although large coils are better for detecting uniform magnetic fields, they are less sensitive to dipoles than are small coils because they encompass more of the sample's fringing fields oriented in the opposite sense to its magnetization (Figure 2a). The result is a Catch-22: once the geometry of the system is set by the coil diameter and the room-temperature access, the samples should be made as large as possible to achieve the optimum signal-to-noise ratio. This reduces the effective spatial resolution of the system (which is set by the diameter of the coils) and means that the sensitivity to small samples is far from optimal.

Now, consider the UHRSSM (Figure 2b). The major difference is that its pickup coil does not encircle the sample, but instead, is brought very close, within 100 μm. This is not an easy task, because the 250-μm diameter, 4 K coil is only separated from the room-temperature environment by a 30-μm thick sapphire window, such that the temperature gradient from coil to sample is several million °C/m! Nevertheless, because the coil is so small, the cryogenic surface area that is exposed to room-temperature thermal radiation is quite small. Thus, the thermal loads on the system are rather modest. The engineering feat of getting a 4 K SQUID to operate within 100 μm of a room-temperature rock eliminates the requirement that the coil encircle the sample, such

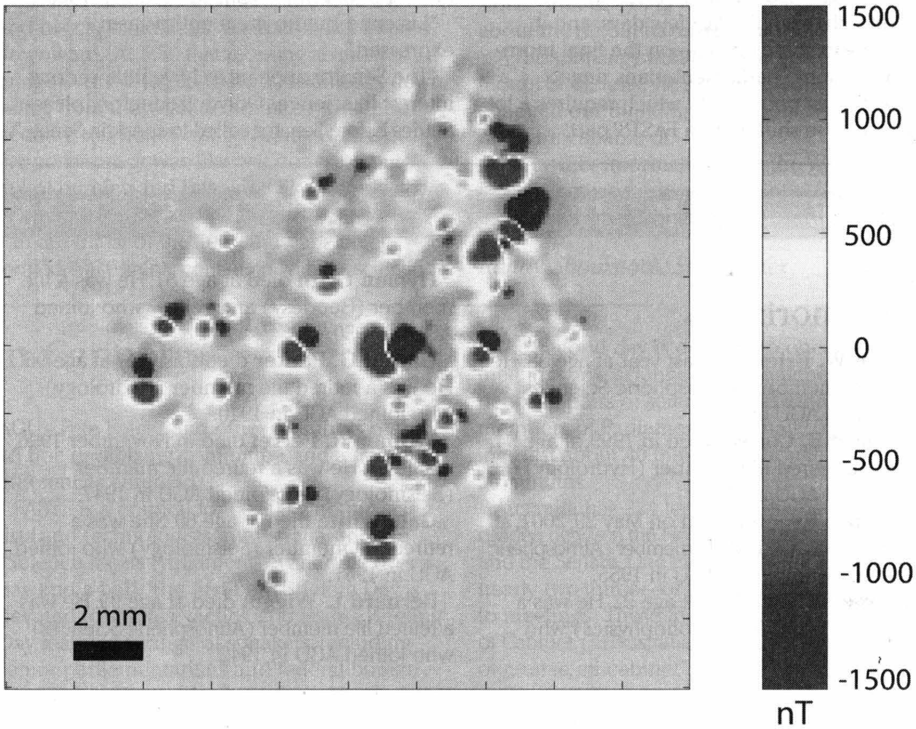

Fig. 1. Ultra High Resolution Scanning SQUID Microscope (UHRSSM) image of a 30-μm thin section of type CR2 carbonaceous chondrite GRA95229, showing the intensity of the out-of-the-page component of the magnetic field as observed ~100 μm above the sample. Numerous, randomly oriented dipolar features associated with chrondrules and matrix are visible. Sample courtesy of H. Connolly. Original color image appears at the back of this volume.

that much less of the fringing field is encompassed (Figure 2b).

Although the field sensitivity of the coil decreases as the coil is made smaller, the magnetic field produced by the dipole increases as $1/r^3$ for distance r between the dipole and coil. If the coil with radius a is at a height a above the sample—which optimizes the tradeoff between sensitivity and spatial resolution—it is easy to show for a uniformly magnetized sample much smaller than a that the signal-to-noise ratio scales as roughly $1/a$. A smaller coil brought closer to the sample produces cleaner signals.

Now, if the coil diameter a is larger than the sample-to-coil distance r (as is the case for the UHRSSM and 2G® SRM), then the spatial resolution of the magnetometer is limited by the coil size. Thus, the dramatic increase in sensitivity resulting from the small size of the coil is accompanied by high spatial resolution. This may seem counter-intuitive, because for many laboratory instruments—for instance, spectrometers or microscopes—spatial resolution and sensitivity are often negatively correlated. But for the imaging of magnetic dipoles, the inverse relationship between sensitivity and coil size in SQUID microscopy persists as long as the coil (and coil-to-sample distance) remains larger than the size of the magnetized region that is being targeted.

The chief limitation of SQUID microscopy comes from the problem of inverting the data output—a spatial grid of vertical components of the magnetic field—into a three-dimensional vector magnetization pattern within the sample, the quantity usually desired by paleomagnetists. This problem is identical to that encountered in the inversion of aeromagnetic field data to a map of lithospheric magnetization. A similar problem is also encountered by those using MFMs and 2G® SRMs, which measure the spatial derivative of the magnetic force field and net magnetization vector, respectively, of the sample. None of these instruments directly measures the spatially heterogeneous magnetization pattern within the target. All suffer from the difficulty that without other constraints, there is no unique magnetization pattern that can be derived from measurements of the magnetic field taken outside the magnetized region.

In practice, this usually does not mean that the inversion is intractable, because many magnetization patterns can be ruled out from other constraints. For instance, only certain magnetization intensities will be plausible given compositional constraints from electron microscopy, microprobe, and other techniques. Also, magnetizations with high amplitudes and spatial frequencies can often be rejected. Scanning electron microscopy and other textural data can be used to localize the boundaries of discrete grains, which are often unidirectionally magnetized, to further reduce the solution space. Measurements of all three components of the net magnetization of the sample with a 2G® SRM will further constrain the solution.

Certain more general criteria can also be required of the magnetization solution. For instance, one can assume that the solution is composed of a grid of many regularly spaced fixed-location dipoles whose intensity and direction are allowed to vary (an "equivalent source" scheme). For samples with a modest number of discrete magnetized grains, the use of a three-axis SQUID microscope, which is currently in development, may also help alleviate the inverse problem.

Initial collaborative work between the Caltech paleomagnetism and Vanderbilt SQUID groups on 1-mm-thick slices and 30-μm-thin sections of Martian meteorite ALH84001 [*Weiss et al.*, 2000] has already

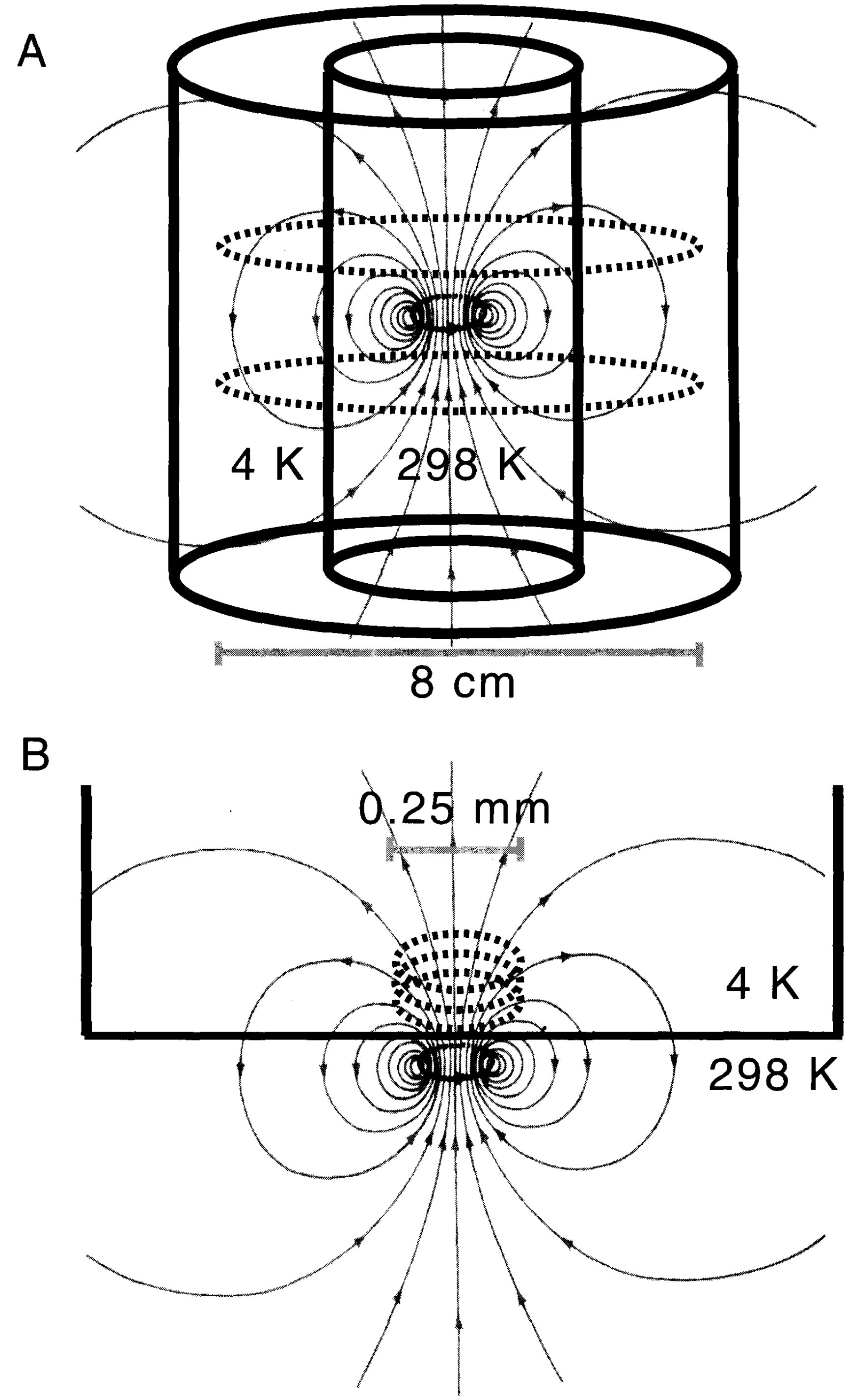

Fig. 2. (a) Schematic cross-section of a 2G Enterprises® Superconducting Rock Magnetometer, showing pair of Helmholtz coils (dashed) held at 4 K and enclosed by shielding. A room temperature sample with a dipolar magnetization oriented upwards, represented as a current loop, is at the center of the coils. The large coils (~8 cm diameter) encompass much of the downward, fringing fields. (b) Schematic cross-section of sensing region of the SQUID Microscope, showing pick-up coils (dashed) held at 4 K, separated from the same sample by a thin (30 μm) sapphire window. The smaller coil (250 μm diameter) encompasses less of the downward, fringing fields. Both diagrams are not to scale.

demonstrated that SQUID microscopy will enable a whole new class of paleomagnetic analyses. Conglomerate, baked contact, and fold tests can be performed on extremely small spatial scales, vastly expanding the utility of these critical geological field tests of magnetic stability. A suite of rock-magnetic and paleomagnetic experiments can be done on individual grains in standard petrographic thin sections at very high rates, allowing the observed magnetic components to be matched with the minerals that are present. This is only the beginning. An improvement in instrumental sensitivity by only a factor of a few—like the magnificent Keck Telescopes, each with a collecting area four times that of the Hale Telescope—is usually considered a major advance that opens new research opportunities. A sudden increase in measuring technique by four orders of magnitude, accompanied by a one to two order-of-magnitude increase in spatial resolution, could be a revolution for paleomagnetism and rock magnetism.

We are currently developing a second-generation LTS SQUID microscope to be located in the magnetically shielded clean laboratory at Caltech. Funds are being sought to make this new instrument open for use by the general paleomagnetic community, and within a few years these instruments should become commercially available.

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OCEAN SCIENCES

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SCOR Announces New Activities

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Roger Revelle had many good ideas during his long and productive career. One of them came to fruition in 1957 in the form of the Scientific Committee on Oceanic Research (SCOR), which the International Council for Science created as its first interdisciplinary body, to promote international activities in oceanography. Revelle served as SCOR's first president from 1957 to 1960. SCOR offers opportunities for scientists from different countries to cooperate in planning and executing international programs in ocean sciences. Over its 44 years in existence, SCOR has sponsored 120 working groups and has actively participated in many of the major international oceanographic projects. Thirty-six nations presently participate as SCOR members.

SCOR Working Groups

National committees and other organizations propose working group activities to SCOR to focus the best expertise worldwide on ocean science issues. Working group meetings are often supplemented with additional workshops and special sessions at meetings of scientific societies to increase involvement of the international ocean science community. Such activities usually result in articles in peer-reviewed journals [e.g., *Millero*, 2000], special issues of journals [e.g., *Hollingworth*, 2000], or books [*Turner and Hunter*, 2001]. Information about current SCOR working groups and other SCOR activities is accessible through the SCOR Web site (http://www.jhu.edu/~scor). Several new working groups have been formed in 2001: Standards for the Survey and Analysis of Plankton, Quantitative Ecosystem Indicators for Fisheries Management, and Marine Phytoplankton and Global Climate Regulation: The *Phaeocystis spp.* Cluster as a Model.

Large-scale Oceanographic Programs

SCOR plays a leading role in planning longer-term, large-scale research programs designed to study the role of the ocean in global change and the effects of global change on the ocean. For example, SCOR was instrumental in developing and sustaining the international Joint Global Ocean Flux Study (JGOFS) and the Global Ocean Ecosystem Dynamics (GLOBEC) project. Now both are co-sponsored by SCOR and the International Geosphere-Biosphere Programme (IGBP), while GLOBEC is also co-sponsored by the Intergovernmental Oceanographic Commission (IOC). Likewise, SCOR is cooperating with the IOC in the Global Ecology and Oceanography of Harmful Algal Blooms program, which recently published a science plan for global research on harmful algal blooms. IGBP's Phase II will be implemented on January 1, 2003, and will feature integrated projects of terrestrial, oceanic, and atmospheric research, as well as interface projects on land-atmosphere, ocean-atmosphere, and land-ocean interactions.

Two of these new projects are being planned and implemented jointly by SCOR and IGBP:

- Surface Ocean-Lower Atmosphere Study (SOLAS)—Processes at and beyond the air-sea interface govern the transfer of chemical species, momentum, and energy between the ocean and atmosphere. More accurate and precise knowledge of the magnitude and temporal variability of such transfers is needed to develop a predictive understanding of global change, including climate change. SOLAS will focus on understanding biogeochemical and physical interactions of the uppermost layer of the ocean (0–200 m) and the portion of the atmosphere above the ocean surface (to about 1 km). SOLAS will serve as IGBP II's ocean-atmosphere interface project. Professor Peter Liss of the University of East Anglia is chairing the international SOLAS Scientific Steering Committee. The World Climate Research Programme and Commission on Atmospheric Chemistry and Global Pollution (CACGP) of the International Association for Meteorology and Atmospheric Sciences are also involved in SOLAS. More information about SOLAS can be found at www.ifm.uni-kiel.de/ch/solas/main.html.
- The Future of Ocean Research in Earth System Science—SCOR and IGBP are cooperating to develop a new framework for future ocean research in Earth system science. The new framework will build on the results of JGOFS and other programs, interface with ongoing projects (that is, GLOBEC, SOLAS, and the Land-Ocean Interactions in the Coastal Zone project), and address new research questions. This activity will serve as the integrated marine project of IGBP II and may result in one or more new projects or augmentations of existing projects. Professor Peter Burkill of the Plymouth Marine Laboratory in the United Kingdom is chairing the first phase of this activity. More information about it can be found on the SCOR Web site.

SCOR has gone through a major transition in the past year, with the retirement of Elizabeth Gross from the SCOR Executive Director position and appointment of a new SCOR president, Robert Duce, and Secretary, Julie Hall. Gross was succeeded by Ed Urban, who